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Title: Mobile chest imaging of neonates in incubators: Optimising DR and CR acquisitions

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Abstract

Introduction: Neonates are a particularly vulnerable patient group with complex medical needs requiring frequent radiographic examinations. This study aims to compare computed radiography (CR) and direct digital radiography (DDR) portable imaging systems used to acquire chest x-rays for neonates within incubators.

Method: An anthropomorphic neonatal chest phantom was imaged under controlled conditions using one portable machine but captured using both CR and DDR technology. Other variables explored were: image receptor position (direct and incubator tray), tube current and kV. All other parameters were kept consistent. Contrast-to-noise ratio (CNR) was measured using ImageJ software and dose-area-product (DAP) was recorded. Optimisation score was calculated by dividing CNR with the DAP for each image acquisition.

Results: The images with the highest CNR were those acquired using DDR direct exposures and the images with lowest CNR were those acquired using CR with the image receptor placed within the incubator tray. This is also supported by the optimisation scores which demonstrated DDR direct produced the optimal combination with regards to CNR and radiation dose. The CNR had a mean increase of 50.3% when comparing DDR direct with CR direct respectively. This was also evident when comparing DDR and CR for in-tray acquisitions, with CNR increasing by a mean of 43.5%. A mean increase of 20.4% was seen in CNR when comparing DDR tray exposures to CR direct.

Conclusion: DDR direct produced images of highest CNR, with incubator tray reducing CNR for both CR and DDR. However, DDR tray still had better image quality compared to CR direct.

Implications for Practice: Where possible, DDR should be the imaging system of choice for portable examinations on neonates owing to its superior image quality at lower radiation dose.

Introduction

To ensure radiographic practice follows the principles of radiation dose protection, it is necessary to perform dose optimisation studies to find and ensure lowest radiation dose whilst maintaining images of diagnostic quality.[1] The need for optimisation is even more essential when imaging neonates due to their growth and quickly dividing cells, placing them at greater risk of cellular mutations and developing cancers in later life.[2] Neonatal radiography is a vital resource in diagnosing and treating the frequent and often life-threatening conditions affecting neonates, with many conditions requiring multiple chest X-rays to diagnose and monitor their progress. [3] Previous studies[4-7] on neonatal optimisation have focused preliminary on acquisition parameters or incubator design and attenuation whilst using one imaging system. A recent study by Allsup and England [8] still found significant variation between existing working practice when imaging neonates highlighting the need to standardise and optimise this area of imaging. An area of variation identified within this study[8] was the different imaging systems (Computed Radiography (CR) and Direct Digital Radiography (DDR)) used and available at each hospital.

Since the introduction of digital systems into clinical practice, there has been a need to review dose optimisation to ensure adherence with the ALARP principle.[1] It has been noted that exposure factors have not evolved and adapted much for digital systems and remain similar to those used with film-screen radiography.[9] Both CR and DDR systems promised radiation dose reduction with superior image quality owing to their high detective quantum efficiency (DQE) and post-processing capabilities.[10] There are many studies comparing CR and DDR in adult patients for various imaging examinations,[11-15] however only one study was found relating CR and DDR to neonatal imaging.[16] This study was a retrospective analysis only comparing image quality between CR and DDR. This study concluded that image quality for DDR was superior to CR; however, there was wide inter-rater variability and no radiation dose measures were provided. In addition, the images used in the comparisons were based on different size and weight neonates, and the location of the image receptor (directly behind neonate or in incubator tray) was not specified.[16] An interesting finding within this study was that technical difficulties were encountered with DDR, this was also seen in previous studies [8,17] whereby the limitations of DDR were noted especially in terms of the digital image receptor being too large to fit within the incubator tray.

The aim of this study was to explore the differences in radiation dose and image quality for neonatal incubator imaging acquired with both CR and DDR portable imaging systems.

Method

This study was conducted using an experimental phantom approach with a neonatal anthropomorphic phantom imaged under controlled conditions.

Imaging equipment and technique

Before commencing the study, quality assurance testing was conducted to ensure results were within accepted tolerances and in accordance with IPEM Report 91.[18] To ensure consistency, the same portable imaging system was used throughout the experiments. All images were acquired using a DR Samsung GM85 portable X-ray machine (MIS Healthcare, London, UK) with half of the images captured using a 25 x 30cm wireless, lightweight S-Detector™ (MIS Healthcare, London, UK) and the other half captured using a Fuji FCR IP cassette type CC (Fujifilm Medical Systems, Tokyo, Japan) and processed using the FCR capsula XL2 image receptor reader (Fujifilm Medical Systems, Tokyo, Japan). The DR Samsung GM85 allows for CR imaging in situations such as when the S-Detector is not in use (broken/serviced) or depending on the size of the detector, some might not be suitable for incubator imaging.[8,16,17] Standard post processing was applied to the acquisitions and no manual adjustments were allowed.

To allow for multiple exposures under consistent conditions, a commercially available Gammex 16 neonatal anthropomorphic phantom was used (Rothband LTD, Haslingden, UK) which simulates a 1 to 2 kg neonate. The phantom was positioned for a standard supine anteroposterior (AP) neonatal chest examination, ensuring the median sagittal plane was coincident with, and at right angles to the incubator tabletop and tray beneath.[20,21] The centering point was fixed in the midline at the level of the sternal angle (between the nipples) **(Figure 1)**, and the collimation remained fixed for all exposures to include the lung apices, lateral margins of both lungs, cardiophrenic and costophrenic sucli in accordance with clinical practice and radiographic textbooks.[20,21] This collimated area (11cm^2) was marked with tape in order to maintain consistency throughout the experiments.

Four parameters (independent variables) were explored thus varied within this experiment. Two different image capture systems were used (CR and DDR), two different image receptor positions *(directly behind neonate and incubator tray)*, three different tube current-times *(0.5, 1 and 1.5)*, and three varying kV settings *(55, 60, 65).* These exposure factor combinations were selected based upon those commonly used within the literature and in clinical practice [4, 7, 8, 20,21] All other acquisition parameters were kept consistent and in accordance to those typically employed in clinical practice and within the literature. [8,20] These included a small focus (0.6mm), 3.2 mm Al total filtration and a source-to-image distance (SID) of 100cm.The above experimental set up resulted in 36 different image acquisitions (**Figure 2**).

Contrast-to-Noise Ratio (CNR)

For this study an objective measure of image quality was used to reduce subjectivity seen within visual image quality evaluations. Contrast to noise (CNR) is a commonly used method of measuring image quality within studies. [9] Jones and colleagues [9] argue that CNR is an appropriate measure of image quality, with image quality having a positive correlation with CNR i.e. the higher the CNR the better the image quality. CNR is especially appropriate for measuring image quality in areas of high inherent contrast, such as the chest, where there is a large range of densities present. [21] CNR takes into consideration the effect of noise on our ability to distinguish objects within the image because visibility depends on contrast (the difference between signals). CNR was therefore calculated by placing a fixed 4mm^2 region of interest (ROI) on two contrasted homogeneous structures within the anthropomorphic neonatal chest phantom images in order to sample the mean and standard deviation of the pixel value. These ROIs are illustrated in **Figure 1** and the above can be seen from the equation:

$$CNR = \frac{S_1 - S_2}{\sigma_1 - \sigma_2}$$

Where S_1 and S_2 are the signal intensities for signal producing structures ROI1 and ROI2, and σ_1 and σ_2 is the standard deviation (pure image noise) at ROI1 and ROI2. To calculate CNR, the images will be extracted from the picture archiving system (PACS) and subsequently used within the specialised software ImageJ (National Institutes of Health, Bethesda, MD).

ImageJ software is regularly used within the literature for similar calculations. [4,22-24] (Lanca et al., 2014; Desai et al., 2010; Jang et al., 2011). ImageJ is an open source image processing tool that is widely available and portable and it establishes the mean pixel values (signal) and the standard deviation (noise) for the ROIs.[25]

Radiation dose assessment

An integral dosimeter in the DDR system and X-ray generator was used to estimate the radiation dose. Dose metrics were recorded as dose area product (DAP) in $cGycm^2$, a unit that is widely understood by clinical staff and therefore provides easier understanding of the data and comparison to clinical practice. DAP will not reflect the effect on the radiation dose by variables from incubator design e.g. attenuation of the incubator tray, however this effect would consequently be captured by CNR. This is because DAP is the absorbed dose to air and is measured leaving the X-ray tube. This means that the radiation dose reading for each combination of exposure factors is identical for CR and DDR and therefore an increase in CNR means superior image quality at equivalent dose.[26]

Optimisation score

In order to determine the optimal combination of imaging conditions, a figure of merit, referred to as *optimisation score* was used. This allowed visualisation of the data to determine highest CNR at lowest possible dose. This was achieved by dividing CNR by DAP in accordance to previous studies that have used this metric. [27,28]

Statistical analysis

Data analysis was carried out by inputting the data into Excel (Microsoft, Redmond, WA) for analysis. Descriptive statistics were reported including mean for CNR, and percentage change used to demonstrate average changes between the independent variables. Pearson's r correlation coefficient was used to measure the strength and direction of any linear relationship between DAP and CNR in order to identify whether CNR increased proportionately with DAP, with >0.75 indicated as excellent, between 0.40-0.75 as fair to good and <0.40 poor. [29]

Results

Of the 36 acquired images from the study, the images with the highest CNR were acquired using the DDR system with the image receptor directly behind the phantom (**Figure 3 and**

Table 1). Conversely, the images with lowest CNR were those acquired using the CR system with the image receptor placed within the incubator tray (**Figure 3)**.

When comparing DDR and CR for images acquired with the image receptor directly behind the neonate, the CNR had a mean increase of 50.3% **(Table 2).** This was also evident when comparing DDR and CR for in-tray acquisitions, with CNR increasing by a mean of 43.5% (**Table 2**). This further demonstrates that CNR on average, doubles for DDR when compared to CNR. Interestingly, on average, an increase of 20.4% was seen in CNR when comparing DDR tray exposures to CR direct. This means that CNR was on average higher for DDR tray exposures compared to direct CR exposures (**Table 3**).

When using the same exposure factor combination, CNR was lower for images acquired using the incubator tray compared with the direct exposures **(Table 1);** this is also reflected in the optimisation scores (**Table 4**). For example, when using the DDR system, with a direct exposure at 60kV and 1mAs exposure factor combination, the CNR was 41 whereas the CNR value for the incubator tray was 26.6. This means the incubator tray reduced CNR by 35% in this scenario. The same is true for CR imaging system where the CNR for a direct exposure at 60kV and 1mAs exposure factor combination was 25.2 and the CNR value for incubator tray was 22.4 casing a reduction of 12%.

The correlation coefficient between radiation dose (DAP) and CNR was higher for DDR (r^2=0.63) in comparison to CR (r^2=0.52), both had a fair to good correlation overall (**Figure 4**). [29]

Discussion

This study was the first to explore the use of both CR and DDR for neonatal imaging using an anthropomorphic phantom under controlled conditions. It consolidated many previous findings together with making several new novel ones. This study found that DDR had superior CNR compared to CR for all acquired images under various conditions. On average, CNR of the images acquired with DDR were double that of CR. This was not surprising as many studies[12, 15, 16, 30] have found DDR to be superior to CR owing to its advanced capabilities and design, such as a higher dynamic quantum efficiency (DQE). A higher DQE is linked to an increase in signal-to-noise radio (SNR) in digital detectors, even at very low exposure factors.

When comparing CNR for image receptor placement (direct verses incubator tray) it can be seen that direct exposures provided a higher CNR. Again, this is an expected finding as incident photons arriving at the image receptor when placed directly behind the neonates (or phantom for this study) would have been attenuated to a lesser degree than if the image receptor was placed the incubator tray. For the exposures made with image receptor in the incubator tray, the incident photons must pass through additional materials including the incubator mattress and table top before reaching the image receptor. This reduction in beam attenuation negatively impacts image quality and is a known phenomenon cited by many studies in neonatal imaging[4-7,31,32]

Inclusion of the incubator tray reduced CNR for both CR and DDR, however, interestingly, CNR for incubator tray exposure using DDR was still higher than the *direct* exposure using CR. This is an interesting finding as it implies that DDR can produce better image quality following attenuation from the mattress and incubator tabletop than a direct exposure using CR. This observed increase in CNR produced with the DDR system may be explained by the greater DQE of the DDR receptor. [33] When considering clinical practice, there is often a requirement to use the incubator tray owing to the fragility of the neonate. A direct exposure requires the neonate to be lifted and placed on a hard image receptor with the possibility of dislodging lines and tubes, in addition to cross-infection risks. The tray on the other hand avoids any disturbance to the neonate and therefore from a safety perspective is advocated. This finding might therefore indicate that it is preferable to perform all image acquisitions for neonates in incubators using DDR digital systems. DDR allows for lower exposure factors to be used than CR and therefore not only increases CNR hence image quality but it requires lower exposure factors to produce images of higher quality.

Another finding from this study which needs consideration when selecting appropriate acquisition parameters for neonatal chest radiography is that CNR decreased in some instances when tube potential was increased from 60 to 65 kV for CR images. Initially, this was considered an anomalous reading however after deliberation; this could also be an inherent feature of the CR imaging receptor. Increasing tube potential increases the penetrating power of the X-ray beam which can decrease contrast. It can be assumed that for very small structures (such as a neonatal chest within this study) that a tube potential of 65 kV may not be required. In addition, CR detectors have a relatively lower modulation transfer function (MTF) compared to DDR receptors which can essentially limit the amount of spatial resolution possible with this receptor. This prevents the CR receptor from being as effective at differentiating between signals at the sample areas.[34] This phenomenon is observed when higher tube potentials are used with this effect more prominent when incident photons are of similar energies. Another explanation for this could be due to the post processing algorithms used by the CR system compared to the DDR system. Similar effects have been recorded in other studies examining image quality in CR imaging systems.[35] This effect could be summarised as an effective loss of contrast due to the over penetration of the phantom due to the high kV combined with the limitation of the CR receptor technology.

This study explored the use of both CR and DDR in neonatal imaging using an anthropomorphic phantom under controlled conditions. Although many interesting findings were made, some limitations need to be considered. Results from this study need to be confirmed using visual image quality analysis to strengthen its findings and to make them more transferable to clinical practice. Having considered this, CNR was used for this study as it is an objective repeatable measure of image quality but also it is very useful in areas of high inherent contrast, such as the chest, where there is a large range of densities present.[21] There are limitations to its use as it does not include the entire imaging chain seen within clinical practice such as the visual evaluation by the observer. However, previous studies that have used the same Gammex phantom[4, 9, 30] and found a strong positive correlation between CNR and visual image quality. Therefore, it can be assumed that this increase found in CNR for DDR would translate to increase in visual image quality too. Jones and colleagues[9] found that images with higher CNR correlated with increased visual image quality when using experienced clinical observers. Our study relied on the automatic post processing functions of the acquisition modality. Such algorithms would have been predefined prior to acquisition and could, if tested experimental, produce different results. It should be accepted that the post processing algorithm is an important variable in any dose optimisation study.

This study should also be repeated using various different CR and DDR portable imaging systems to reinforce and confirm findings. Lastly, it would be useful to determine other dose metrics for this study, such as absorbed dose or effective dose in order to identify the risk associated with the exposure as oppose to a measure in air.

Conclusion

This study was the first study to compare DDR and CR imaging systems for neonatal imaging using anthropomorphic phantoms under controlled conditions. This study found that DDR produced images of higher image quality than CR, with CNR for DDR, on average, double that of CR. In addition, incubator tray reduced CNR for both CR and DDR compared to when using a direct exposure. However, interestingly, the incubator tray exposures using DDR had an increase in CNR compared with a CR direct exposure. This questions whether CR should be used for neonatal imaging due to the requirement for increased radiation dose to improve image quality. This finding is especially important if imaging neonates requires using the incubator tray, as CR tray produced the worst image quality at each exposure/dose setting.

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Figure(s)

Figures

Figure 1

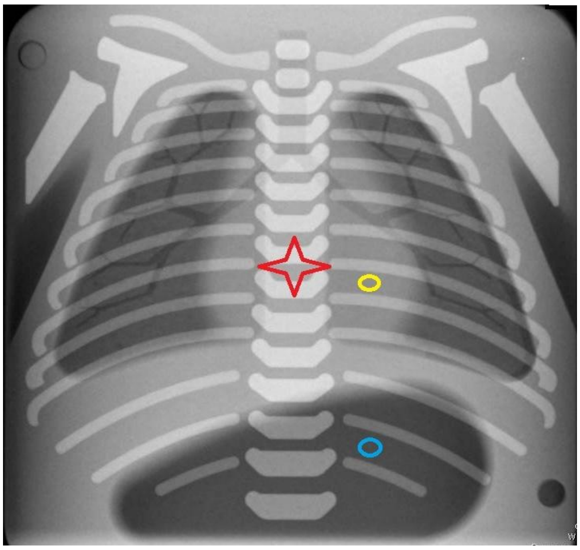

Figure 2

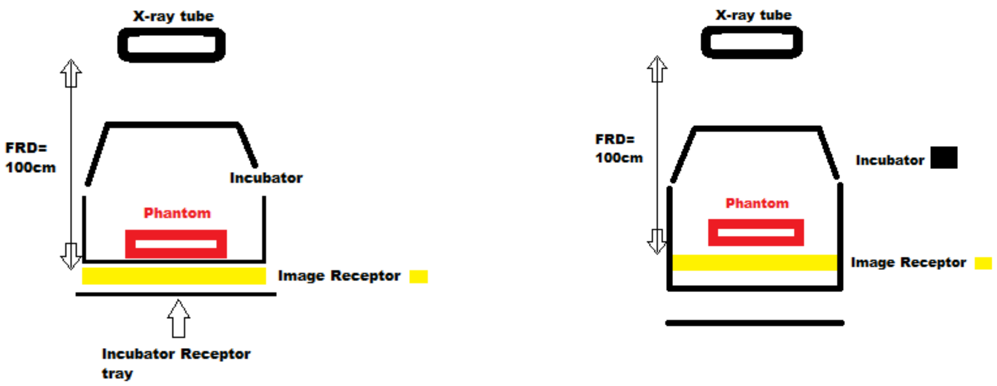

Figure 3

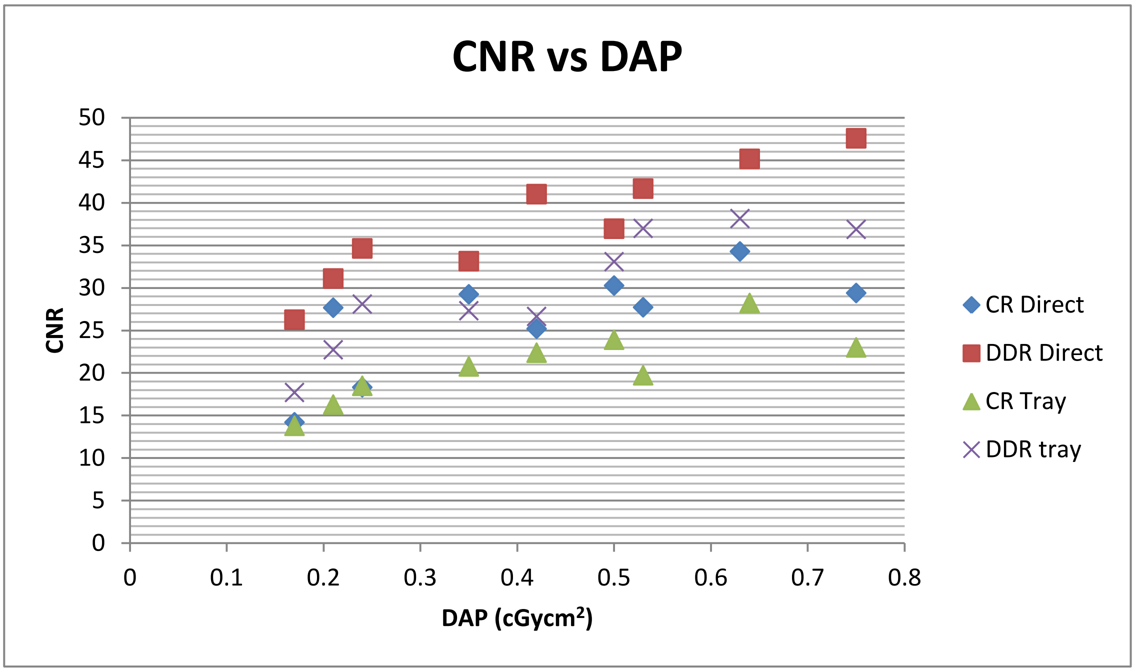

Figure 4

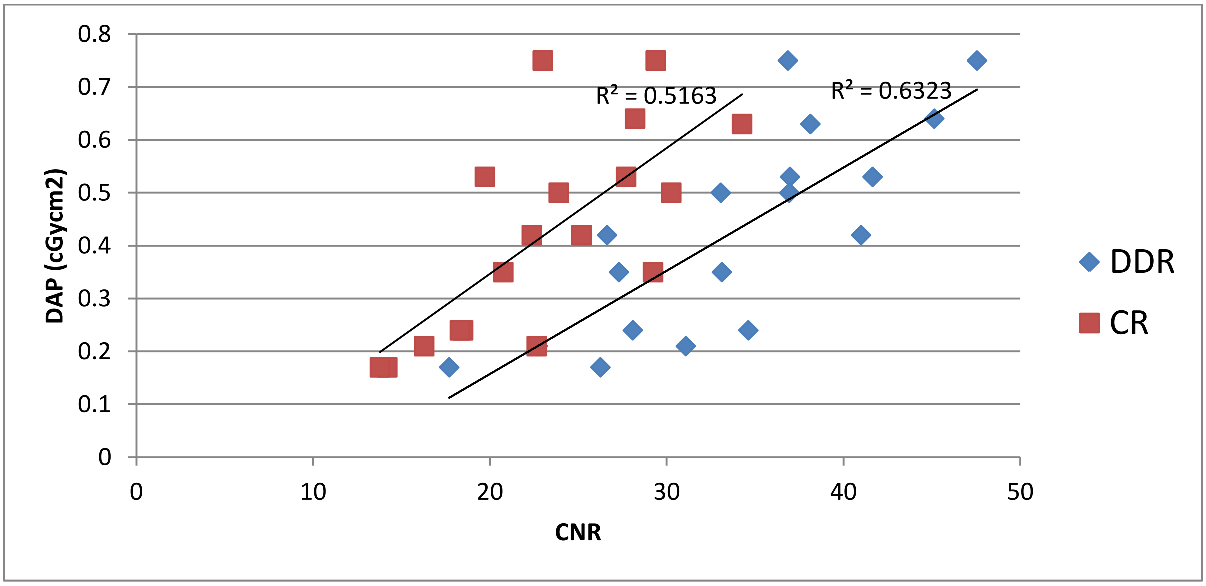

Figure captions

1. Figure 1 - resultant CXR image demonstrating the location of ROI 1 (yellow) and ROI2 (blue), with red star denoting centring point for all acquisitions

2. Figure 2 - A diagram explaining the experimental setup for direct and in-tray X-ray acquisitions.

3. Figure 3 – A scatterplot illustrating the relationship between DAP and CNR for the various different imaging conditions.

4. A graph illustrating the correlation between DAP and CNR for both DDR and CR.

Table(s)

Table 1. Summary of CNR values of each image acquisition of both DDR and CR system.

	Direct Digital Radiography (DDR)					
mAs	**0.5**		**1.0**		**1.5**	
kV	**Direct**	**In-tray**	**Direct**	**In-tray**	**Direct**	**In-tray**
55	26.3	17.7	33.1	27.3	41.7	37.0
60	31.1	22.7	41.0	26.6	45.1	38.1
65	34.6	28.1	37.0	33.1	47.6	36.9
	Computed Radiography (CR)					
55	14.2	13.8	29.2	20.8	27.7	19.7
60	22.7	16.3	25.2	22.4	34.3	28.2
65	18.3	18.5	30.3	23.9	29.4	23.0

Table 2. Differences (%) in CNR between DDR and CR images.

IR Position	Tube potential (kV)	Tube-current-time (mAs)	% change in CNR for DDR	Mean % change
Direct	55	0.5	84.9	50.3
		1.0	13.3	
		1.5	50.3	
	60	0.5	37.0	
		1.0	62.8	
		1.5	31.7	
	65	0.5	89.1	
		1.0	22.1	
		1.5	61.8	
In-tray	55	0.5	28.4	43.5
		1.0	31.5	
		1.5	87.5	
	60	0.5	39.5	
		1.0	19.0	
		1.5	35.2	
	65	0.5	51.9	
		1.0	38.3	
		1.5	60.3	

Table 3. Differences (%) in CNR between DDR in-tray images and CR direct images.			
Tube potential (kV)	Tube-current-time (mAs)	% change in CNR for DDR	Mean % change
55	0.5	24.7	20.4
	1.0	-6.6*	
	1.5	33.5	
60	0.5	0.0	
	1.0	5.7	
	1.5	11.3	
65	0.5	53.4	
	1.0	9.3	
	1.5	25.4	
* for combination CR direct provided a higher CNR			

Table 4. A table demonstrating the five images with the highest image quality at lowest dose (optimisation score)							
Image	**CNR**	**IR position**	**Tube potential (kVp)**	**Tube-current-time (mAs)**	**DAP ($cGycm^2$)**	**IR type**	**Optimisation Score**
1	26.3	Direct	55	0.5	0.17	DDR	154.5
2	31.1	Direct	60	0.5	0.21	DDR	148.1
3	34.6	Direct	65	0.5	0.24	DDR	144.3
4	28.1	In-tray	65	0.5	0.24	DDR	117.1
5	22.7	In-tray	60	0.5	0.21	DDR	108.2